Higgs and Drell-Yan at NNLOPS

Work done in collaboration with

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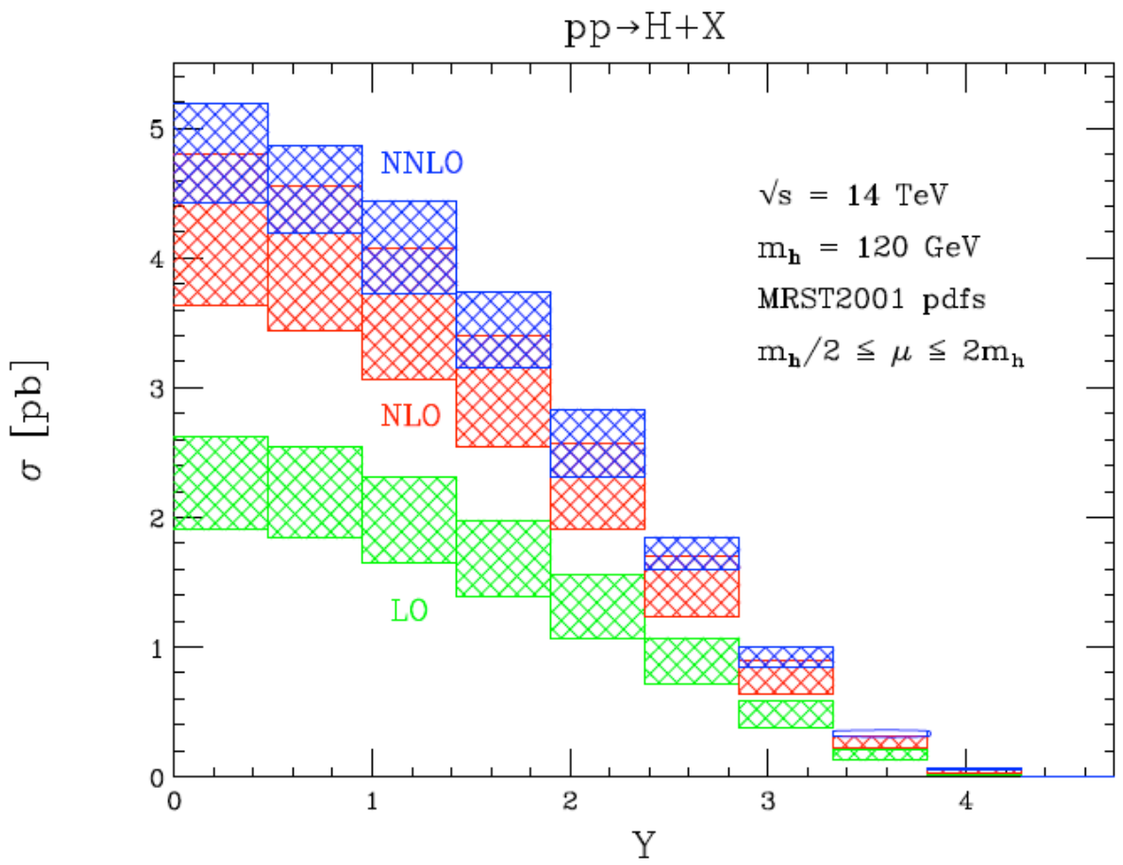
NNLO

Why NNLO?

- high precision requires NNLO (e.g. Drell Yan)
- sometimes NLO corrections very large. Even moderate precision requires NLO (paramount example Higgs)
- NNLO is the frontier: first $2 \to 2$ calculations available



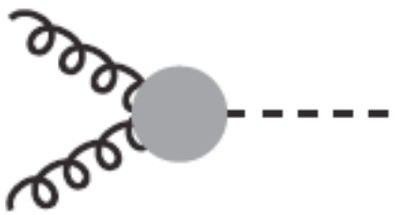
Anastasiou et al. ’04-’05

Why merge NNLO + parton shower?

- realistic exclusive description of the final state (including MPI, resummation effects, hadronisation, U.E.) with state-of-the-art perturbative accuracy
- clearly a MUST for the upcoming LHC physics programme

NNLO

Example: ingredients for Higgs at NNLO



loops: 0 1 2

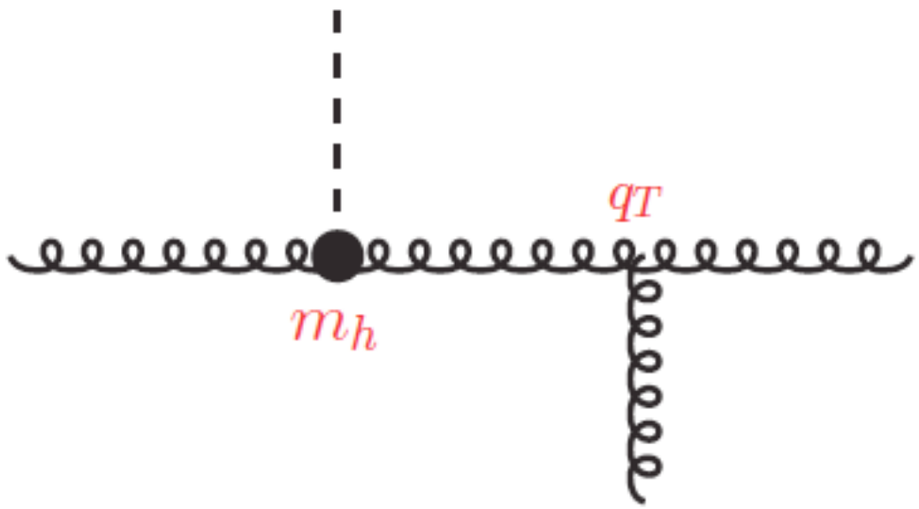
loops: 0 1

✓ ✓

loops: 0

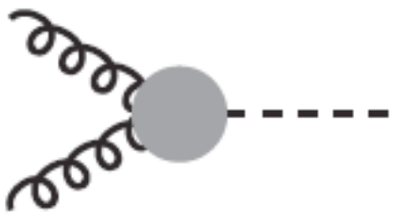
✓

- ✓ NLO Higgs plus one jet calculation in POWHEG
- ✗ but standard NLO Higgs plus one jet calculation diverges without a transverse momentum cut on the jet



NNLO

Example: ingredients for Higgs at NNLO



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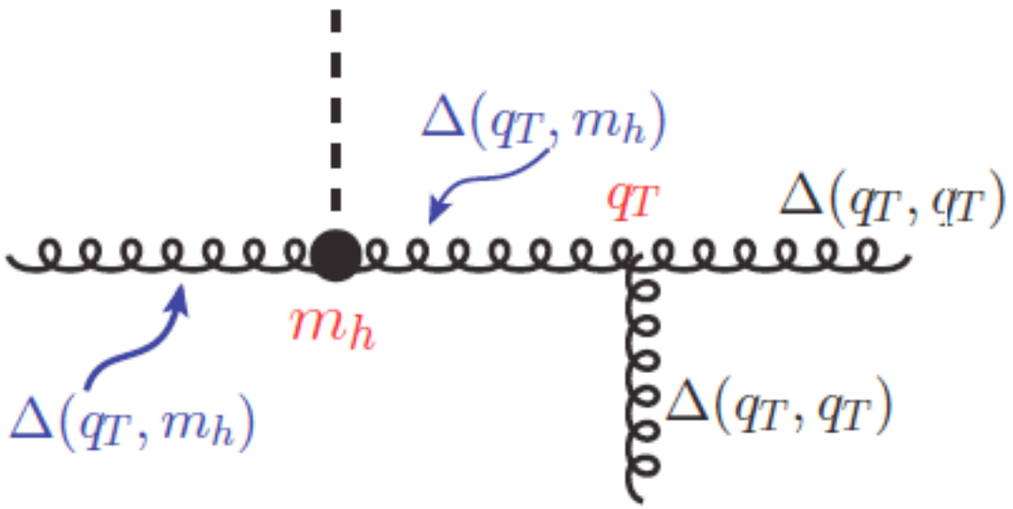
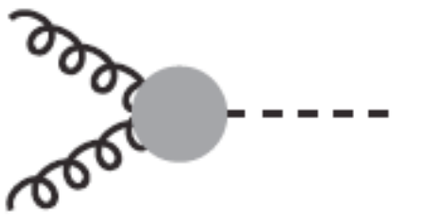
- ✓ NLO Higgs plus one jet calculation in POWHEG
- ✓ NLO H+1jet calculation upgraded with MiNLO is finite upon integration over q_T



Hamilton et al. 1206.3542

NNLO

Example: ingredients for Higgs at NNLO



loops: 0 1 2

✓ ✓

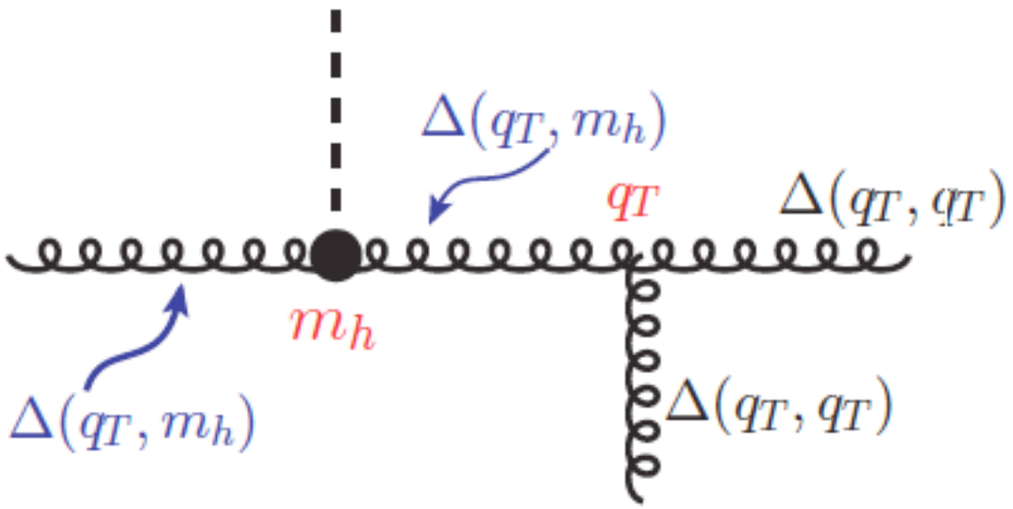
loops: 0 1

✓ ✓

loops: 0

✓

- ✓ NLO Higgs plus one jet calculation in POWHEG
- ✓ NLO H+1jet calculation upgraded with MiNLO is finite upon integration over q_T
- ✓ MiNLO procedure can be formulated such that the integral is the NLO inclusive Higgs cross-section

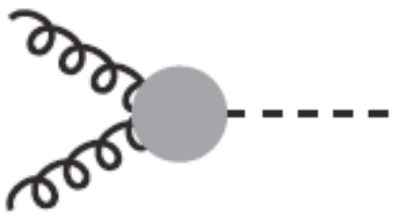


Hamilton et al. 1206.3542

Hamilton et al. 1212.4504

NNLO

Example: ingredients for Higgs at NNLO



loops: 0 1 2

✓ ✓

loops: 0 1

✓ ✓

loops: 0

✓

✗ still missing double virtual contribution

☛ can get the two-loop double virtual from an available NNLO calculation?

NNLOPS generator with MiNLO

Hamilton et al. 1309.0017

For Higgs production, the Born kinematics is fully specified by the Higgs rapidity. So consider the following distributions:

$\left(\frac{d\sigma}{dy}\right)_{\rm NNLO}$ → inclusive Higgs rapidity computed at NNLO

$\left(\frac{d\sigma}{dy}\right)_{\rm HJ-MiNLO}$ → inclusive Higgs rapidity from H+1jet-MiNLO

Since H+1jet-MiNLO (HJ-MiNLO) is NLO accurate, it follows that

$$\frac{\left(\frac{d\sigma}{dy}\right)_{\rm NNLO}}{\left(\frac{d\sigma}{dy}\right)_{\rm HJ\text{-}MiNLO}} = \frac{c_2\alpha_s^2 + c_3\alpha_s^3 + c_4\alpha_s^4}{c_2\alpha_s^2 + c_3\alpha_s^3 + d_4\alpha_s^4} \approx 1 + \frac{c_4 - d_4}{c_2}\alpha_s^2 + \mathcal{O}(\alpha_s^3)$$

Thus, re-weighing HJ-MiNLO+Pythia results with this factor one obtains NNLO+PS accuracy

Proof of NNLO accuracy

Theorem:

A parton level Higgs boson production generator that

1) is accurate at $O(\alpha_s^4)$ for all IR safe observables that vanish with the transverse momenta of all light partons, and

2) that also reaches $O(\alpha_s^4)$ accuracy for the inclusive Higgs rapidity distribution,

achieves the same level of precision for all IR safe observables, i.e. it is fully NNLO accurate.

Proof of the theorem

- take any infrared safe observable F. It's value is $\langle F \rangle = \int d\Phi \frac{d\sigma}{d\Phi} F(\Phi)$
- because of infrared safety, F has a smooth limit when the momenta or all light partons vanish. This limit can depend only on the Higgs rapidity, call it F_y.
- write $\langle F \rangle = \langle F - F_y \rangle + \langle F_y \rangle$
- since $\langle F - F_y \rangle$ vanishes when momenta of all light partons vanish, it is described at NNLO accuracy
- on the other hand $\langle F_y \rangle = \int dy' \frac{d\sigma}{dy'} F_y(y')$ and so it is also NNLO accurate
- thus, $\langle F \rangle = \langle F - F_y \rangle + \langle F_y \rangle$ is NNLO accurate

q.e.d.

Proof of NNLO accuracy

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The HJ-MiNLO generator satisfies property 1). The re-scaling with $\mathcal{W}(y)$ trivially also guarantees property 2).

Finally, since POWHEG preserves NLO accuracy of the HJ calculation, further emissions from the shower give rise to terms beyond $O(\alpha_s^4)$

Variants

Hamilton et al. 1309.0017

It is possible to define variants of the method. One defines

$$d\sigma = d\sigma_A + d\sigma_B \qquad d\sigma_A = d\sigma \cdot h(p_T) \qquad d\sigma_B = d\sigma \cdot (1 - h(p_T))$$

with h a function between 1 and 0, e.g. $h(p_T) = \dfrac{(c\,m_H)^\gamma}{(c\,m_H)^\gamma + p_T^\gamma}$

And one can re-weight the HJ-MiNLO events with the factor

$$\mathcal{W}(y, p_T) = h(p_T) \frac{\int d\sigma_A^{\mathrm{NNLO}} \delta(y - y(\Phi))}{\int d\sigma_A^{\mathrm{MiNLO}} \delta(y - y(\Phi))} + (1 - h(p_T))$$

The idea is to distribute the virtual correction only in the low-p_t region (in the high p_t region no improvement)

Uncertainty definition

Vary

- $\mu_R = \mu_F$ in NNLO by factor 2 up and down around $m_H/2$ (3 scales)
- μ_R, μ_F in HJ-MiNLO event generation by factor 2 up and down avoiding $\mu_R/\mu_F = 1/4, 4$ (7 scales)

Take the envelope of the 21 scale choices

Conservative motivation to take scale variations both in NNLO and in HJ-MiNLO independently is to consider uncertainties in normalization (NNLO) and shape (MiNLO) as independent

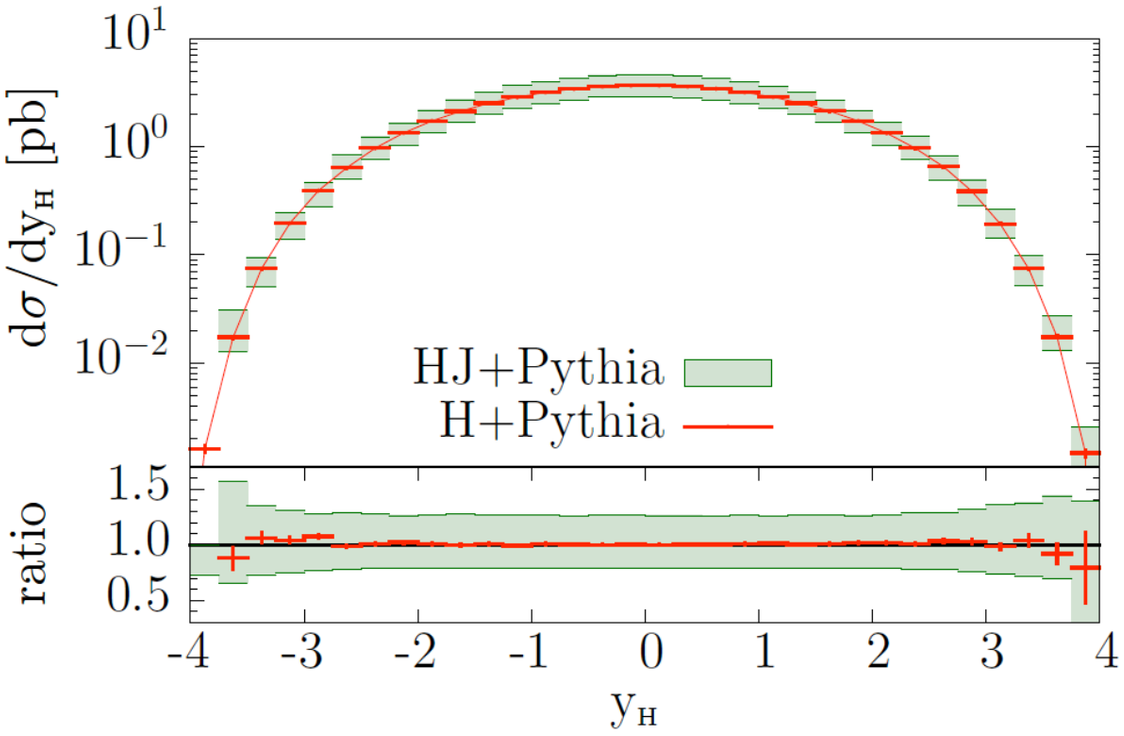
(similar to efficiency method for cross-sections with jet-veto)

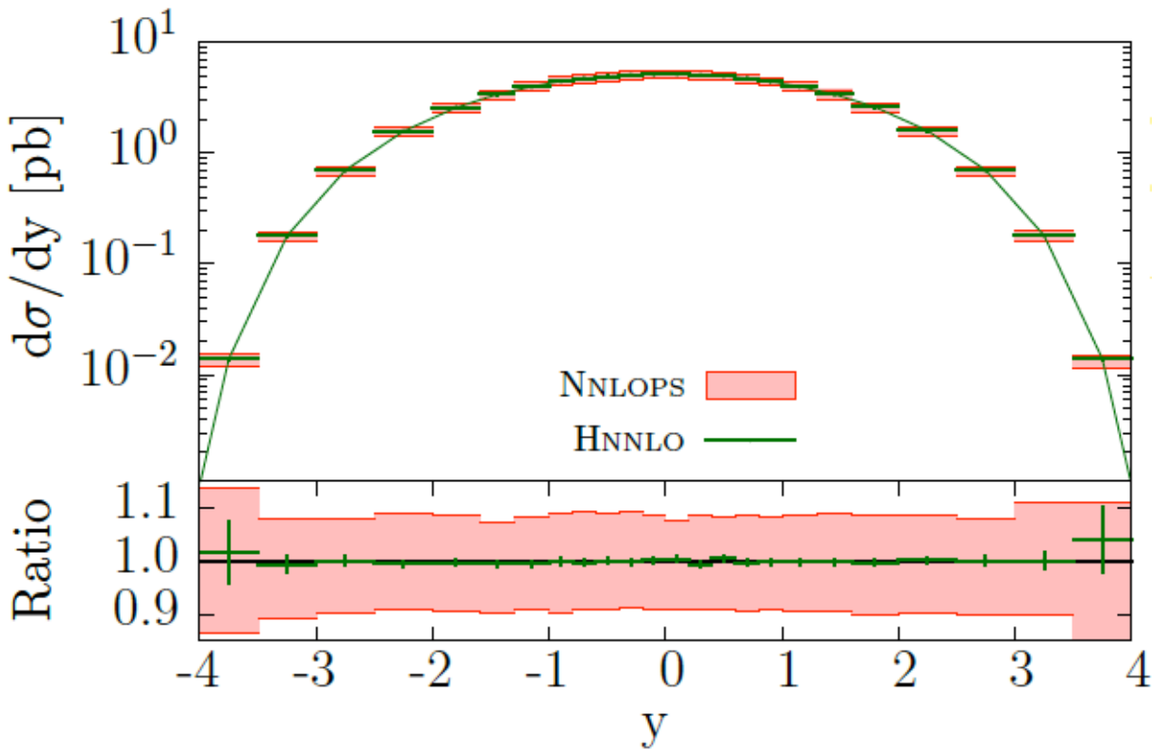
Settings

LHC 8 TeV, m_H=125.5 GeV, MSTW8NNLO everywhere, Pythia6 (320 tune), parton level only, jets: anti-k_t R=0.5

Higgs production at NNLO+PS

Higgs rapidity: comparison to HNNLO [Catani, Grazzini]





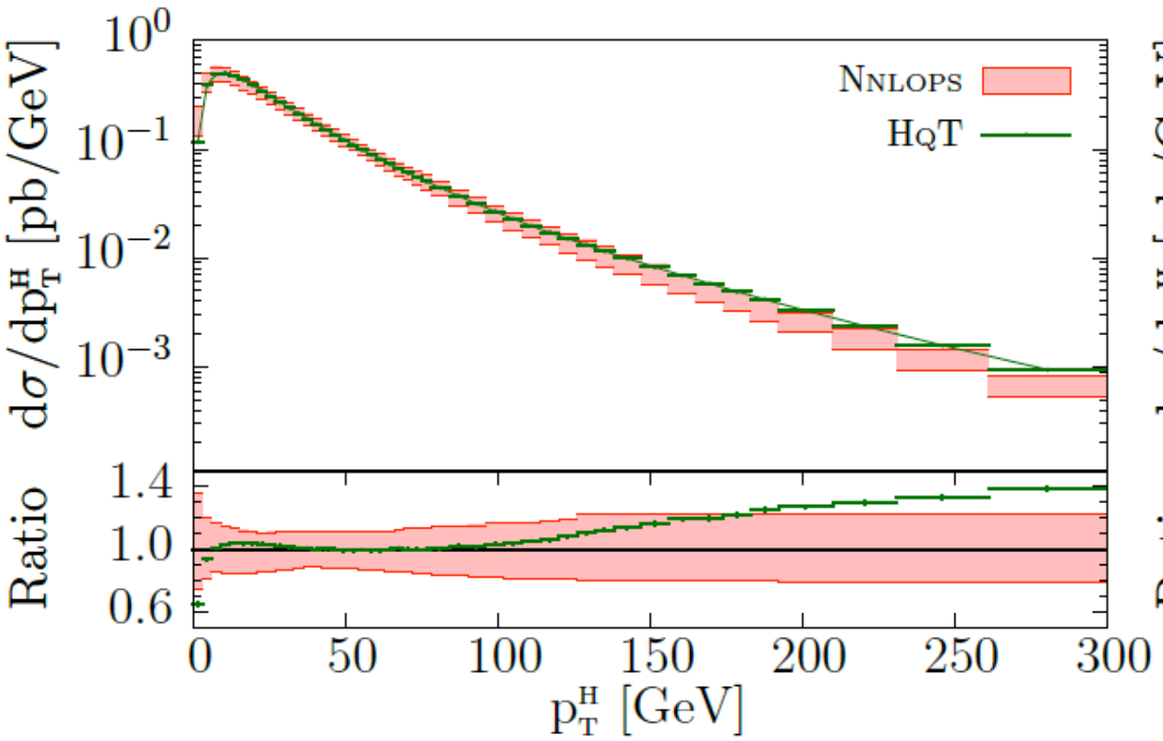
Accuracy:

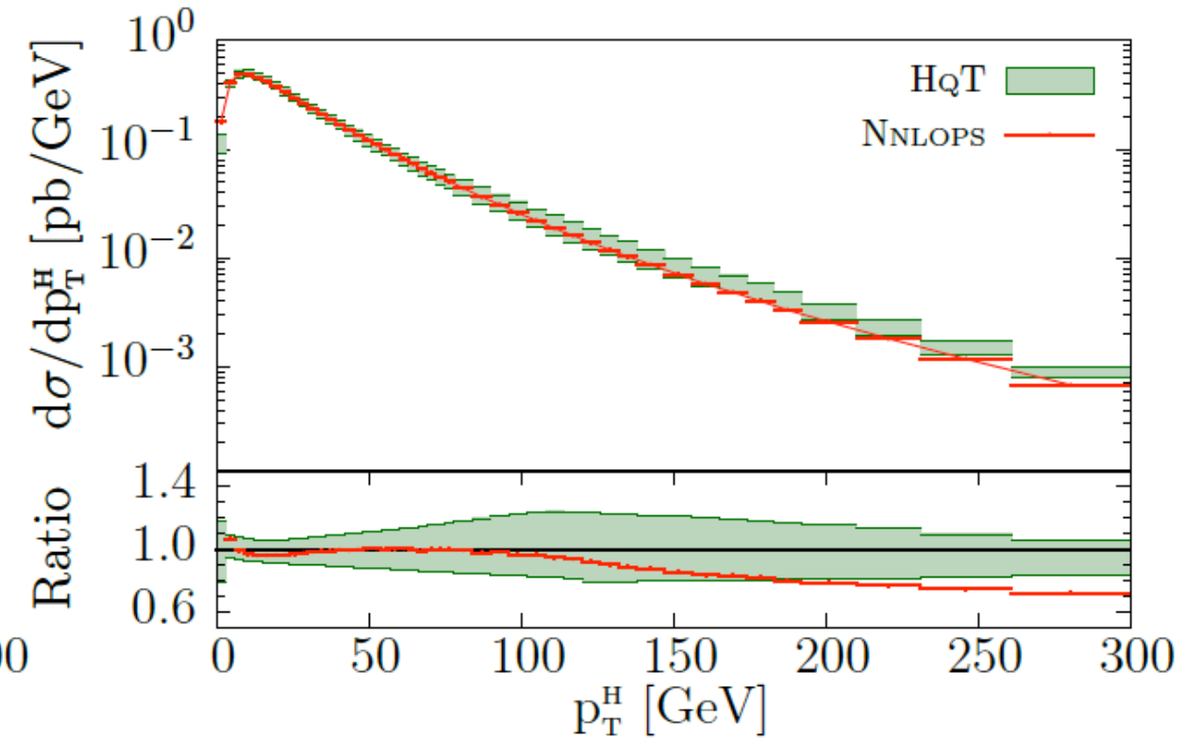
(left) NLO+PS: ~ 30%

(right) NNLO+PS: ~ 10%

Higgs production at NNLO+PS

Higgs transverse momentum: comparison to HqT





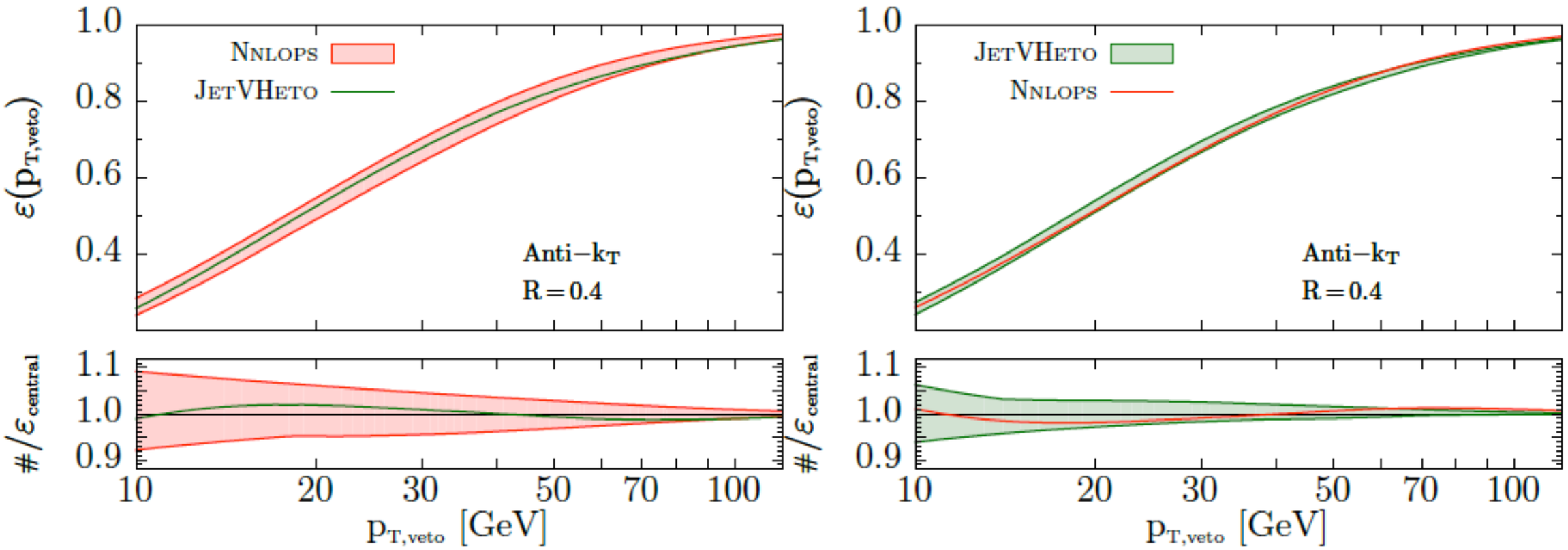
- HqT: state-of-the-art NNLO+NNLL

  [Bozzi,Catani, De Florian, Ferrera, Grazzini, Tommasini]

- good agreement at small/moderate p_T
- large p_T: Higgs+1jet@NNLO will allow to say more

Higgs production at NNLO+PS

Jet-veto efficiency: comparison to JetVHeto



- JetVHeto: state-of-the-art NNLO+NNLL [Banfi, Salam, Monni,GZ]
- agreement at the level of 2-3% everywhere

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

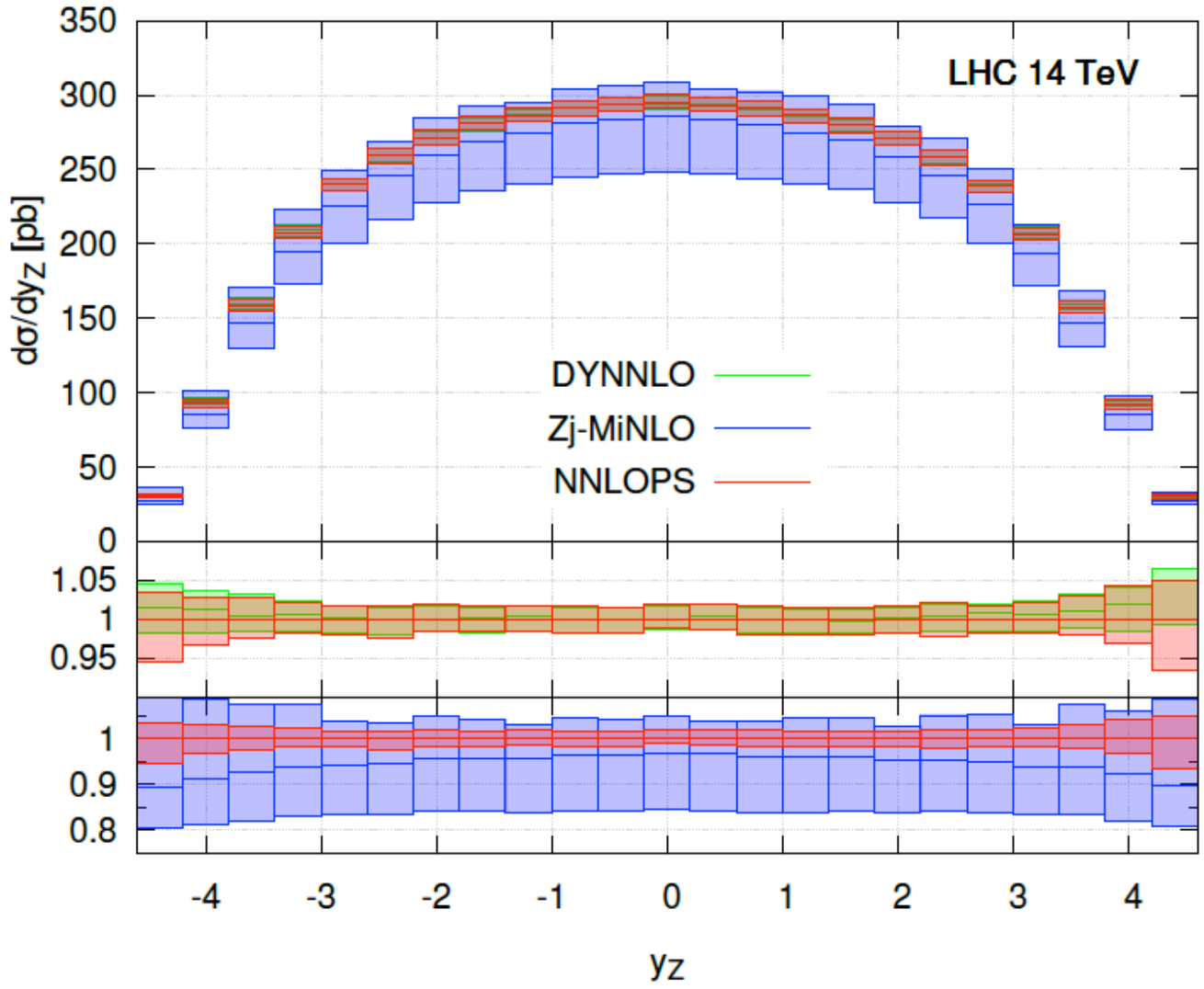
Extension to Drell-Yan is relatively straightforward

- because of spin-correlations in the decays of the boson need to perform a rescaling in terms of the variables specifying the Born process pp → 2 leptons
- this requires a rescaling in terms 3 independent variables, rather than just the Higgs rapidity as in Higgs production
- freedom in the choice of variables, but important to choose variables/binning so that bins are populated uniformly, we use
  - ✓ rapidity of the Z boson y_Z
  - ✓ angle between electron and beam in frame where $p_{l,Z}=0$
  - ✓ variable related to dilepton-invariant mass $\mathrm{atan}((m_{ll}^2-M_Z^2)/\Gamma_Z M_Z)$

DY at NNLOPS: see also Hoche, Hi and Prestel 1405.3607

Drell Yan at NNLOPS

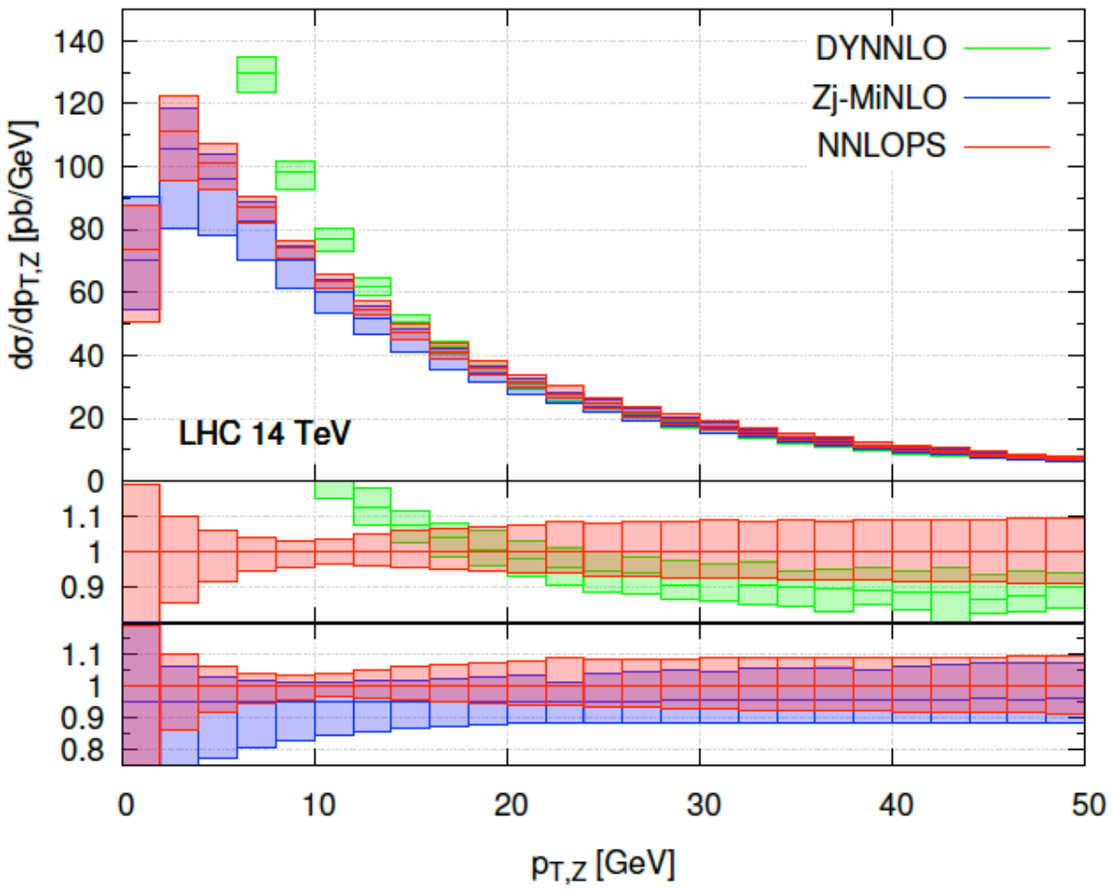
Karlberg, Re, Zanderighi preliminary

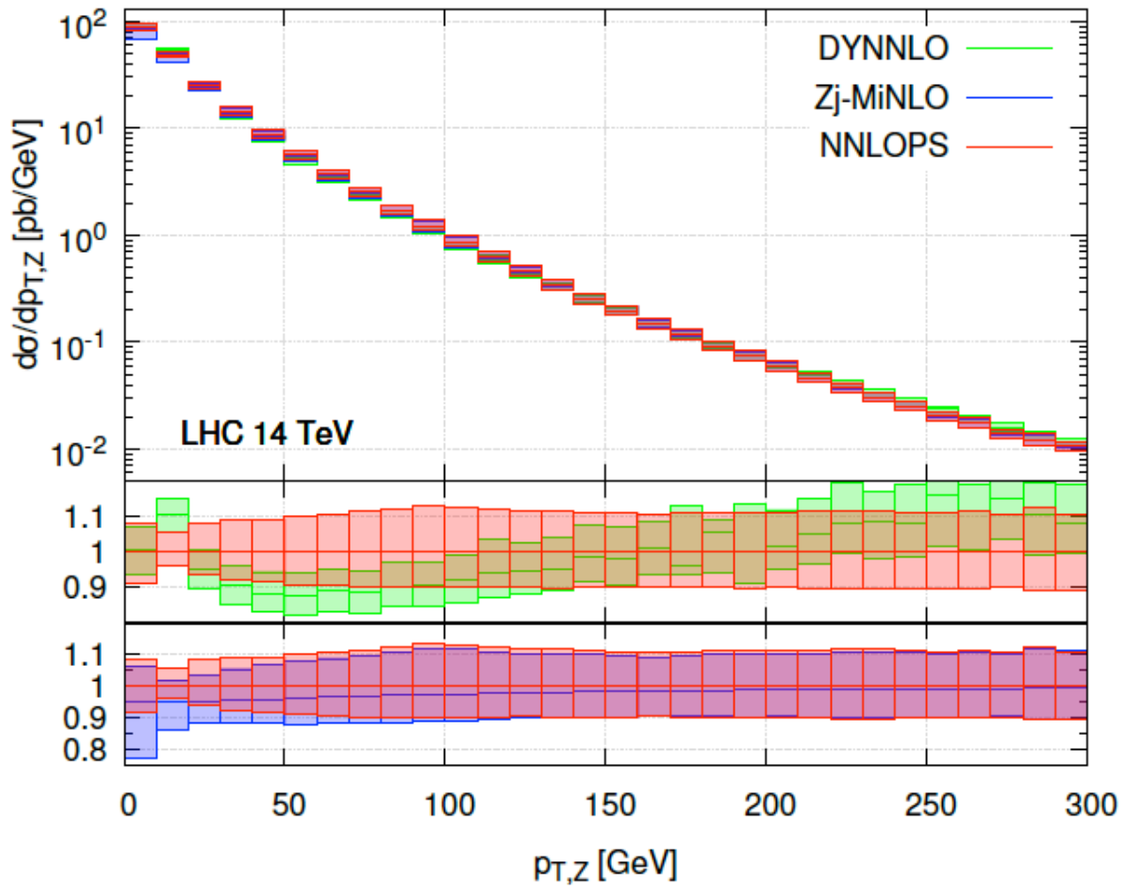


- validation: agreement with DYNNLO for y_Z (and mll and θ_l)
- reduction of uncertainty wrt to ZJ+MiNLO

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary



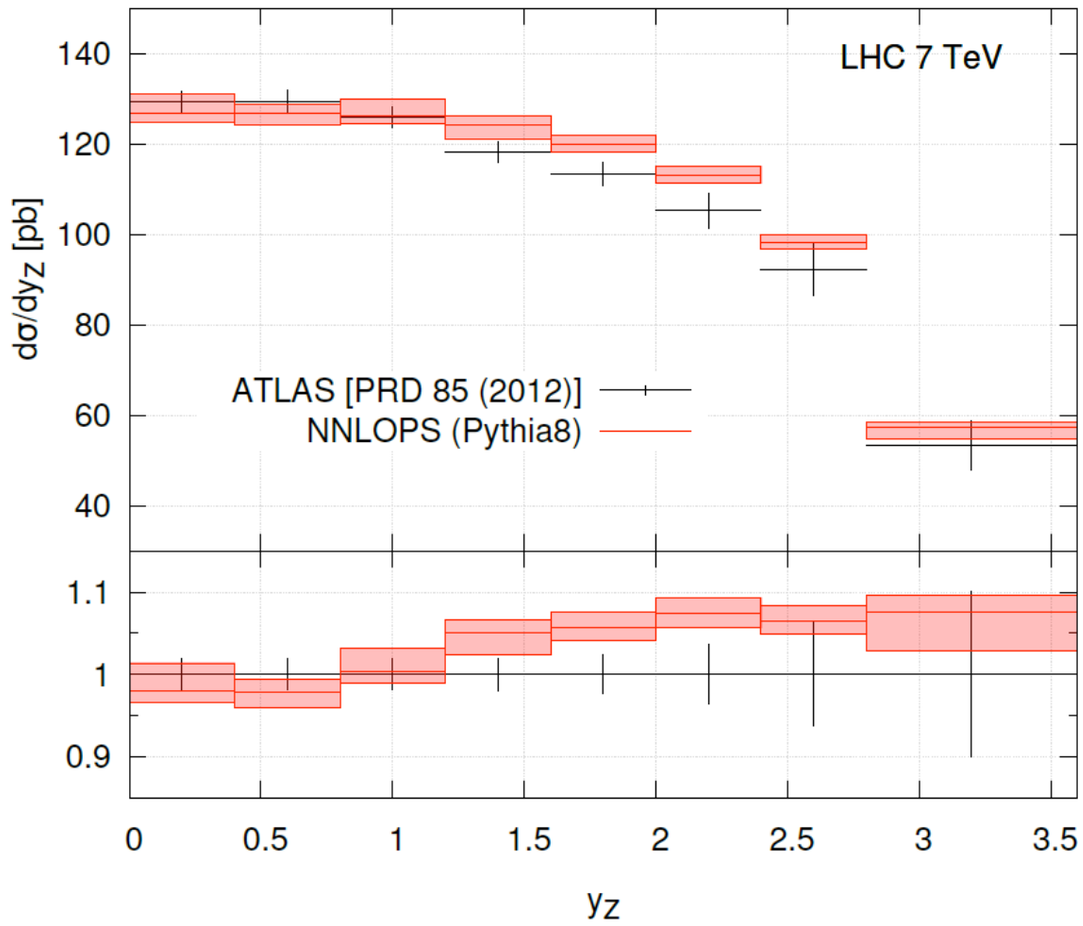


- NNLOPS smooth behavior where DYNNLO diverges
- DYNNLO uncertainty too small at low p_t
- at high p_t all calculations comparable

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

Comparison to data



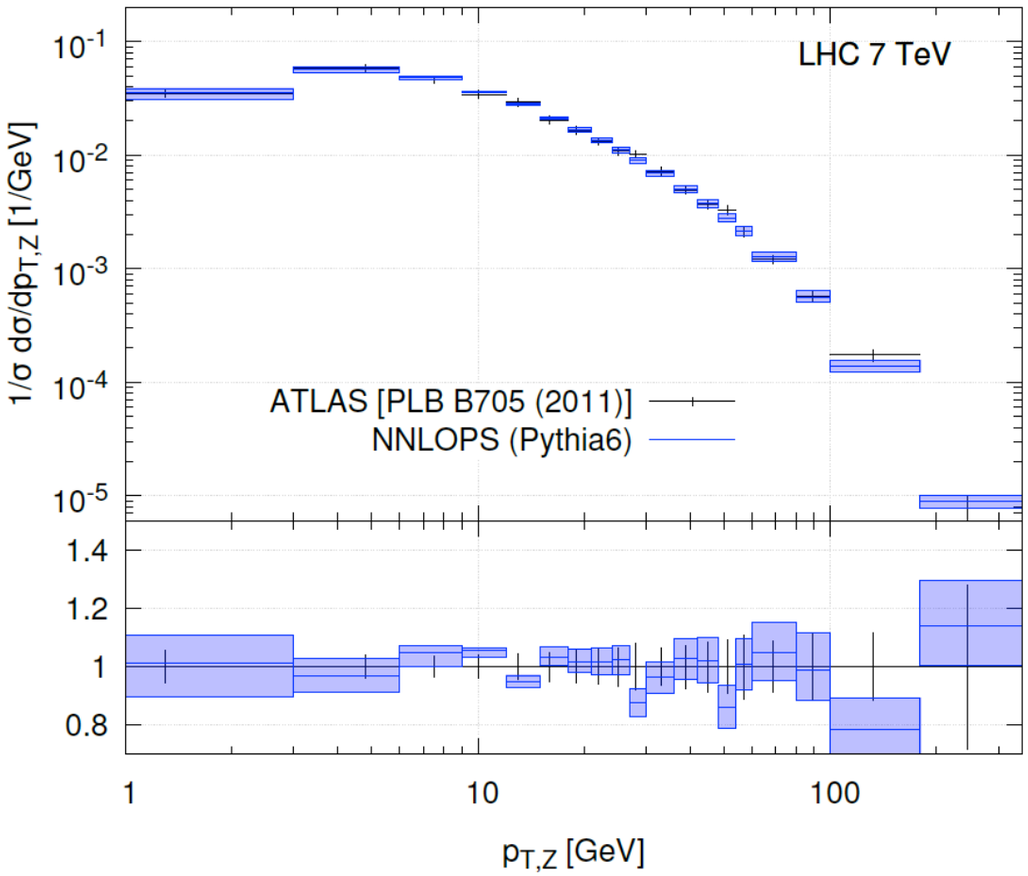
More comparisons to data available soon [Karlberg et al. 1406.xxxx]

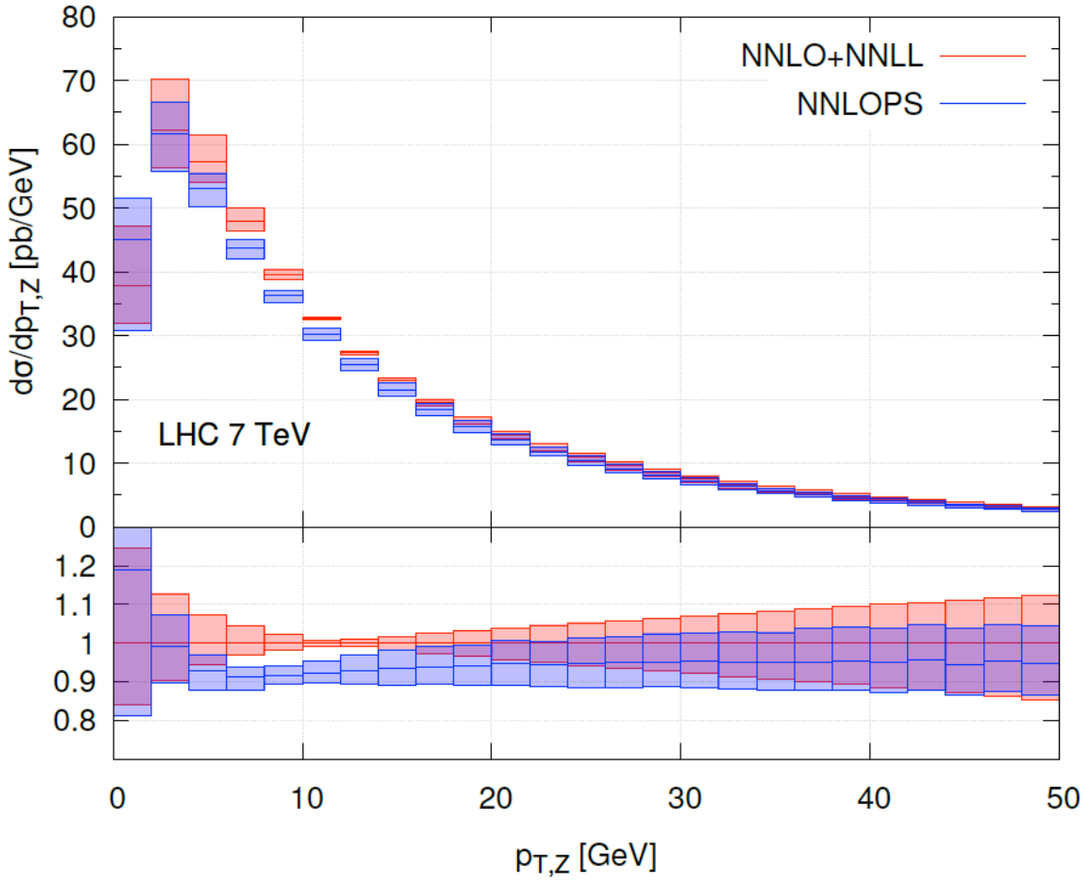
Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

Comparison to ATLAS data and NNLL+NNLO resummation for $p_{t,Z}$

[Bozzi et al. 1007.2351]



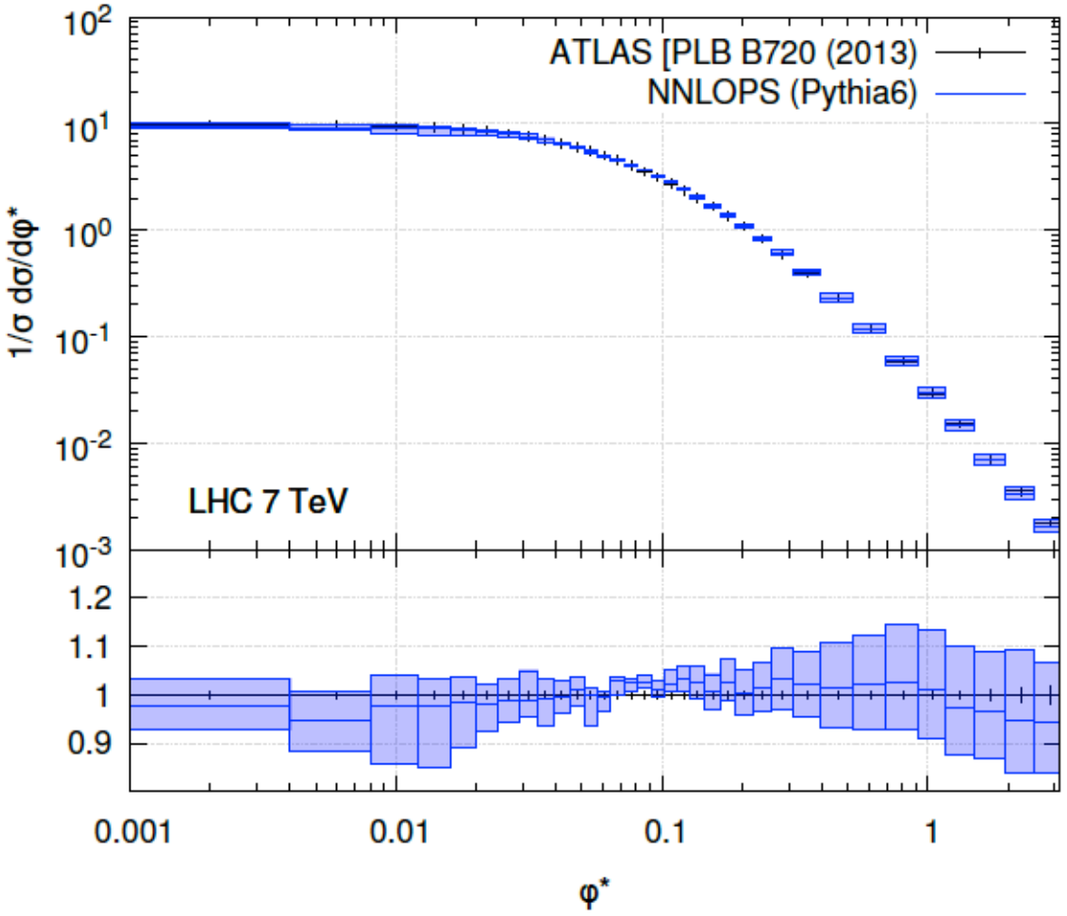


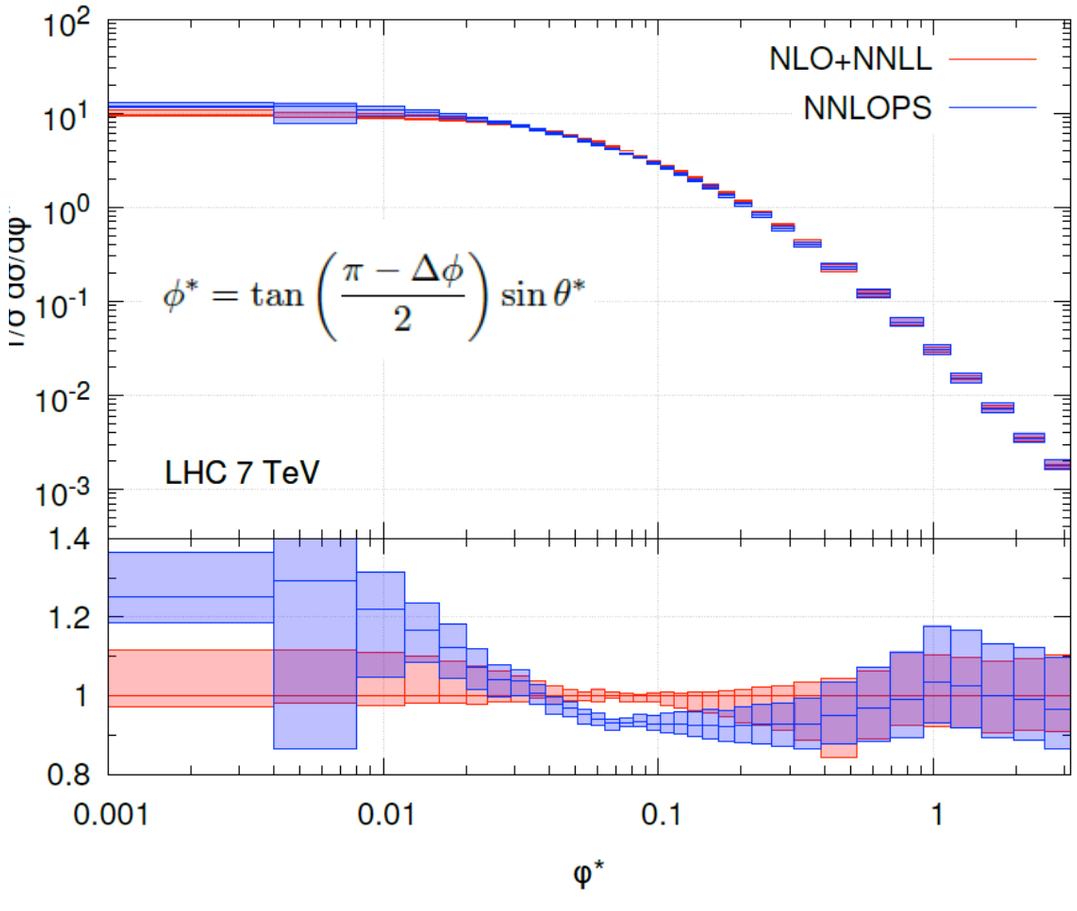
- good description of data
- agreement with resummation not perfect at small $p_{t,Z}$

Drell Yan at NNLOPS

Karlberg, Re, Zanderighi preliminary

Comparison to ATLAS data and NNLL+NNLO resummation [Banfi et al. 1205.4760] for φ*





- good description of data (but hadronization effects important)
- agreement with resummation not perfect at small φ^*

Conclusions

- MiNLO born as a scale-setting procedure à-la CKKW, but inclusion of Sudakov form factor turn out to have great benefits and deep implications

  [no need for generation cuts or Born suppression factors+ allows merging of different jet-multiplicities (0-jet and 1-jet for now)]

- first NNLOPS generator for Higgs and Drell-Yan production

  Public code in POWHEG-BOX V2: HJ process. ZJ/WJ soon

- next: inclusion of mass-effects in Higgs production at NNLOPS

Extra Slides

F. A. Q.

But will the parton shower preserve the NNLO accuracy?

But where, in HJ-MiNLO, is the one-loop virtual correction to inclusive Higgs production?

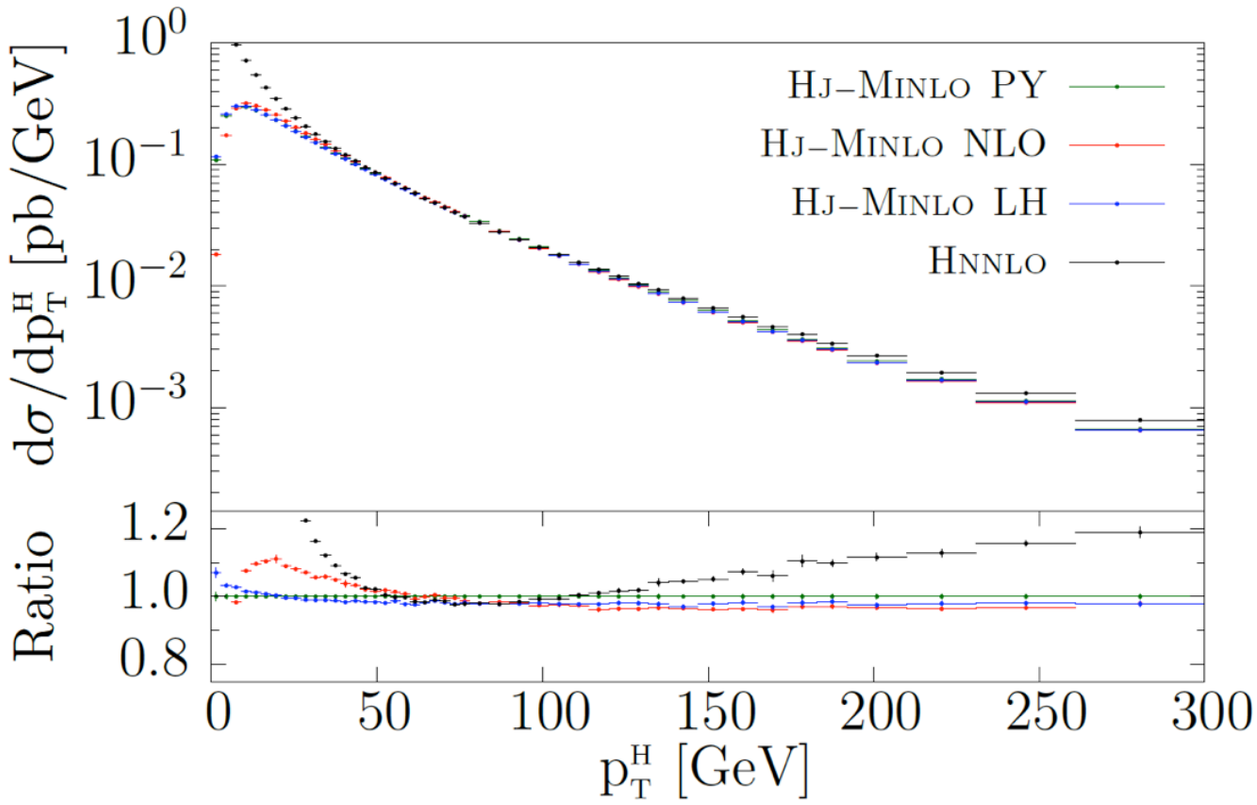
Can this method be generalized to other processes?

Is this really NNLO+PS in the same sense as POWHEG and MC@NLO are NLO+PS?

To make HJ-MiNLO NLO accurate for inclusive Higgs production, you need the B_2 coefficient for the Higgs q_T resummation. But B_2 depends on the observable. How can this be generic?

Higgs production at NNLO+PS

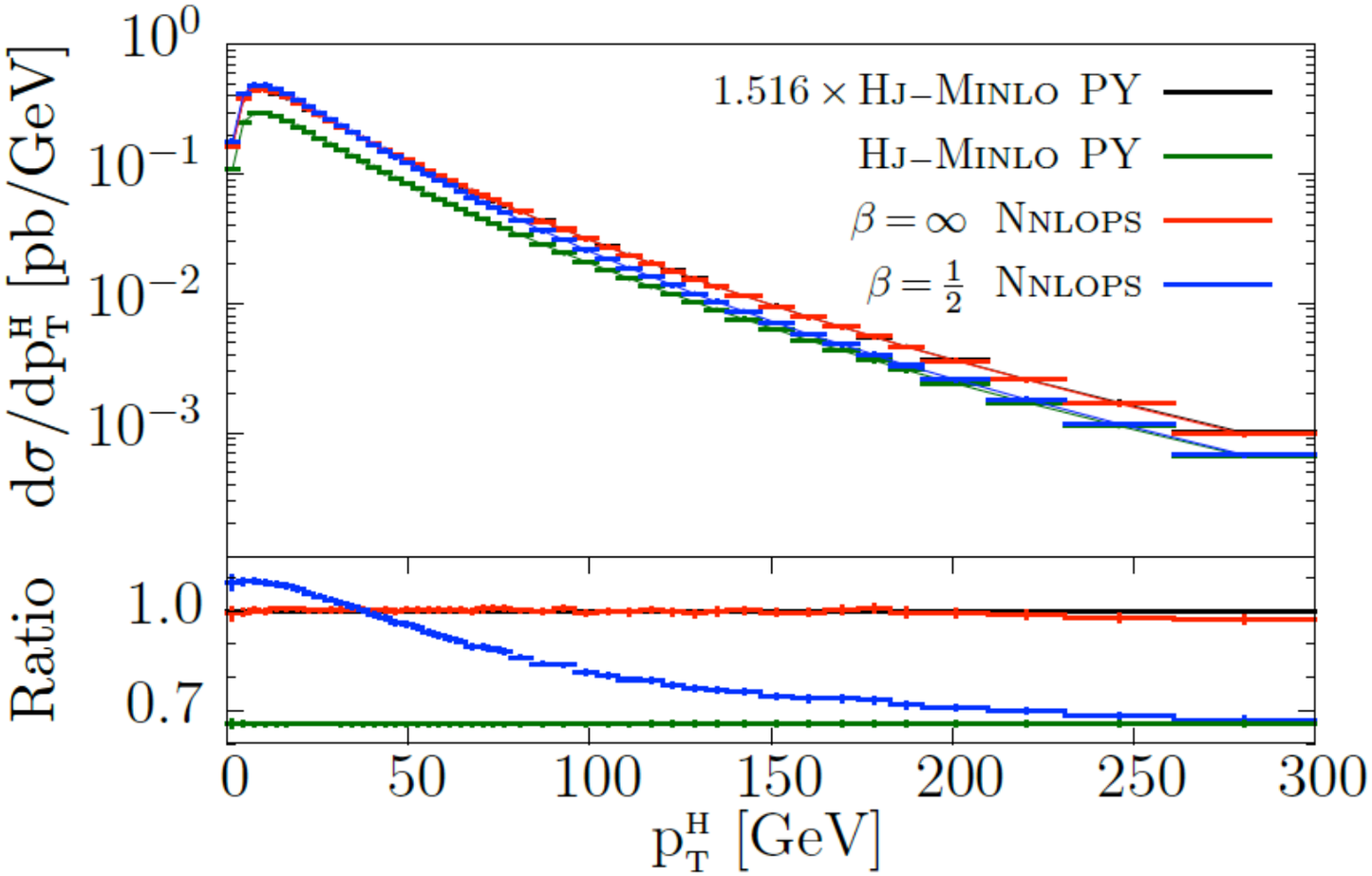
Higgs transverse momentum: various level of the NLO simulation



- excluding the very low p_T region all predictions accurate to $O(\alpha_s^4)$
- HNNLO divergent at small p_T and less steeply falling at high p_T (because of fixed scale)
- good agreement between PY/NLO/LHE at intermediate/high p_T

Higgs production at NNLO+PS

Higgs transverse momentum: at NNLO level of the simulation



- β = ∝ amounts to almost an overall K-factor rescaling
- finite β spreads the NNLO correction in the low transverse momentum region (our default)